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Mid-Infrared Spectra of Be Stars

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Abstract. We present medium-resolution ($R \sim 600$) mid-infrared (8-13.3μm) spectra of γ Cas and a coadded spectrum of nine Be stars. A large number of lines have been observed and identified in these spectra, including 39 hydrogen recombination lines in the spectrum of γ Cas. In the majority of our spectra, all of the observed lines are attributable to hydrogen recombination. Two additional sources, β Lyr and MWC 349, show [Ne II] emission and β Lyr also displays [He I] emission. We tabulate the effective line strength and line widths for the observed lines, and briefly discuss the physical implications of the observed line series. We also use a simple model of free-free emission to characterize the disks around these sources.

1. Introduction

The observations presented here were taken using SCORE (van Cleve et al. 1998) at the Cassegrain focus of the Hale 5-m telescope.[1] SCORE is a novel medium resolution mid-infrared spectrograph built originally as a proof of concept of the Infrared Spectrograph (IRS) short-hi module for SIRTF. It uses cross-dispersion to obtain a 7.5-15μm spectrum in a single exposure. The obtained spectrum has a resolution of ~600, with a $1'' \times 2''$ slit. SCORE also makes use of a second MIR array for slit-viewing, which both simplifies source acquisition during observing and provides information for photometric calibration. All of these observations were made using standard beam-switched chopping and nodding techniques. The 1σ sensitivity at 11.0μm in 100 seconds of integration for our instrument is roughly 90mJy. The MIR seeing for these observations was typically $1''$.

The individual integrations of each object were stacked, and the N-band spectra were extracted using SCOREX, software designed to optimally extract the spectrum from the cross-dispersed format of SCORE (Smith et al. 1998). These spectra were then calibrated using observed spectra of standard stars (Cohen, et al. 1992) to properly remove spectral features from the sky background.

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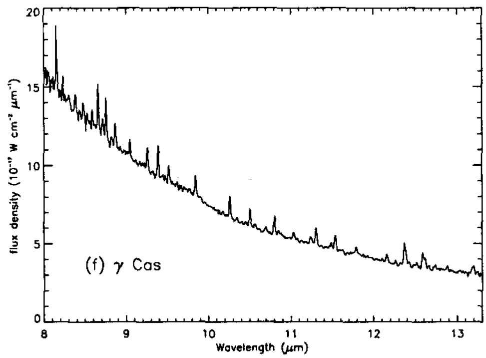

Figure 1. The reduced spectra of γ Cas.

The observed spectra from these standard stars were taken at nearly the same airmass as our observed objects, as even relatively small differences in airmass result in different strengths of atmospheric features, leading to inaccurate subtraction of background features from our calibrated spectra.

2. Observed Spectra of Be stars

In Figure 1, we present the reduced spectra of γ Cas. This spectra clearly shows the presence of a large number of emission lines, all of which are attributable to hydrogen recombination; these lines are listed in Table 1. In Figure 2, we show a similar spectra which consists of the coadded spectra of 9 Be stars. Because the majority of our sources displayed very similar spectra, we use this to show clearly the presence of many of the weak lines with good SNR. In two of our sources, β Lyr and MWC 349, emission from Neon ([Ne II] 12.88μm) was observed, and Helium emission was also observed in β Lyr. These sources were not included in the coadded spectra shown in Figure 2, as their spectra were very different than our pure hydrogen spectra sources.

3. Discussion

Both the continuum emission and the line emission are likely to arise in a warm stellar envelope. The presence of so many high-level hydrogen transitions provides valuable insight into the origin of line emission. The line strengths are inconsistent with optically thin line emission (Hummer & Storey 1987), and therefore must originate at optical depths of $\sim$ 1. Such optically thick emission is the product of the Planck function, the area of emission, and the line width. Since the Planck function of a gas with temperatures consistent with the production of such high H recombination lines decreases with wavelength, and our observations show no clear trend in line width with wavelength, the surface area must be increasing with wavelength (see Waters et al., these proceedings,

Table 1. Data on observed lines – γ Cas, Aug 1998

Transition	λ_{theory}	λ_{obs}	$\Delta\lambda$	F_ν
H 7→6	12.372	12.369 ± 0.0031	9.53 ± 2.643	1.09 ± 0.363
H 9→7	11.309	11.307 ± 0.0015	6.57 ± 1.391	1.20 ± 0.328
H 10→7	8.760	8.759 ± 0.0031	6.13 ± 2.804	2.19 ± 1.328
H 11→8	12.387	12.394 ± 0.0065	7.71 ± 6.266	0.45 ± 0.433
H 12→8	10.504	10.504 ± 0.0018	6.85 ± 1.670	1.25 ± 0.400
H 13→8	9.392	9.393 ± 0.0015	6.85 ± 1.386	1.79 ± 0.474
H 14→8	8.665	8.666 ± 0.0028	7.69 ± 2.543	2.33 ± 1.174
H 14→9	12.587	12.589 ± 0.0022	6.37 ± 1.716	1.05 ± 0.370
H 15→8	8.155	8.154 ± 0.0010	4.20 ± 0.832	4.96 ± 1.311
H 15→9	11.540	11.540 ± 0.0017	8.03 ± 1.555	1.11 ± 0.283
H 16→9	10.804	10.803 ± 0.0015	6.39 ± 1.314	1.41 ± 0.383
H 17→9	10.261	10.260 ± 0.0018	7.62 ± 1.620	1.28 ± 0.361
H 18→9	9.847	9.846 ± 0.0016	6.38 ± 1.349	1.74 ± 0.494
H 18→10	13.188	13.197 ± 0.0034	6.70 ± 2.798	0.74 ± 0.410
H 19→9	9.522	9.522 ± 0.0023	2.70 ± 2.071	0.74 ± 0.721
H 19→10	12.611	12.615 ± 0.0021	5.63 ± 2.998	0.87 ± 0.615
H 20→9	9.261	9.262 ± 0.0035	9.17 ± 3.226	0.88 ± 0.433
H 20→10	12.157	12.157 ± 0.0044	9.53 ± 4.018	0.46 ± 0.259
H 21→9	9.047	9.048 ± 0.0017	2.27 ± 2.738	2.17 ± 5.413
H 21→10	11.792	11.793 ± 0.0043	7.66 ± 3.738	0.52 ± 0.334
H 22→9	8.870	8.873 ± 0.0057	6.64 ± 5.096	1.34 ± 1.340
H 22→10	11.492	11.488 ± 0.0032	4.14 ± 4.405	0.36 ± 0.537
H 23→9	8.721	8.726 ± 0.0172	---	---
H 23→10	11.243	11.241 ± 0.0054	7.70 ± 4.900	0.39 ± 0.334
H 24→9	8.594	8.594 ± 0.0021	2.10 ± 2.184	2.02 ± 3.400
H 24→10	11.033	11.034 ± 0.0061	8.01 ± 5.466	0.43 ± 0.383
H 25→9	8.485	8.489 ± 0.0050	6.74 ± 4.387	1.43 ± 1.237
H 25→10	10.855	10.849 ± 0.0099	---	---
H 26→9	8.391	8.390 ± 0.0036	4.28 ± 3.611	1.61 ± 1.737
H 26→10	10.701	10.694 ± 0.0096	---	---
H 27→9	8.309	8.307 ± 0.0053	---	---
H 27→10	10.567	10.580 ± 0.0091	---	---
H 28→9	8.236	8.240 ± 0.0018	3.65 ± 1.244	3.58 ± 1.550
H 28→10	10.451	10.453 ± 0.0248	---	---
H 29→9	8.173	Blended with 15→8		
H 29→10	10.348	10.334 ± 0.0049	---	---
H 30→9	8.116	8.107 ± 0.0040	6.80 ± 3.654	1.71 ± 1.218
H 30→10	10.258	Blended with 17→9		
H 31→10	10.177	10.181 ± 0.0074	6.71 ± 6.115	0.28 ± 0.332

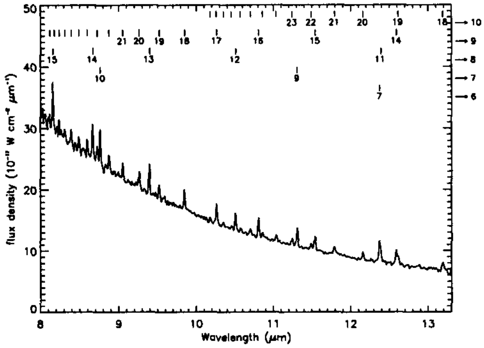

Figure 2. The spectrum produced by coadding nine Be star spectra. Several weak lines are clearer in this summed spectra.

for ISO spectra of γ Cas). This in turn implies a density gradient, in order to explain why the observed line strengths remain roughly constant within each series.

The continuum emission is also informative. The infrared excess in these sources arises from free-free radiation from the warm gas in the circumstellar disk. By using a model including photospheric emission, optically thin free-free radiation, and optically thick free-free radiation, we have determined some basic parameters for the circumstellar disks of our sources. In the case of γ Cas, we find a shell radius (R_{sh}) of 6.00 ($\pm$.13)$R_\star$, an electron density (n_e) of 4.57 (+.33/−.21) $\times 10^{11}$ cm^{-3}, and a shell temperature (T_{sh}) of 2.68 (+.15/−.14) $\times 10^4$K.

In addition to our spectrum of γ Cas, we have obtained spectra for 10 other Be stars, including the two peculiar objects β Lyr and MWC 349. These spectra and additional discussion can be found in Rinehart et al. (1999).

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